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HEATSTORE SWITZERLAND: New Opportunities of Geothermal District Heating Network Sustainable Growth by High Temperature Aquifer Thermal Energy Storage Development

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ABSTRACT

HEATSTORE is a GEOTHERMICA ERA-NET co-funded project, aiming at developing High Temperature (~25°C to ~90°C) Underground Thermal Energy Storage (HT-UTES) technologies by lowering the cost, reducing risks, improving the performance, and optimizing the district heating network demand side management at 6 new pilot and demonstration sites, two of which are in Switzerland, plus 8 case studies. The European HEATSTORE consortium includes 24 contributing partners from 9 countries, composing a mix of scientific research institutes and private companies.

The Swiss consortium, developing HEATSTORE in Switzerland, involves of two industrial partners (Services Industriels de Geneva - SIG and Energie Wasser Bern - EWB) and four academic partners (Universities of Geneva, Bern, Neuchâtel and ETH Zurich), with support from the Swiss Federal Office of Energy. The aims are to develop two demonstration projects for High Temperature Aquifer Thermal Energy Storage (HT-ATES) in the cantons of Geneva and Bern such that industrial waste heat can be converted into a resource.

This paper presents the results of the first year of activities in the Swiss projects. The activities planned cover subsurface characterization, energy system analysis, surface implementation design, legal framework improvement and business modelling to ensure the sustainability of the projects. This approach is supported by large industrial investments for subsurface characterization. Two wells, down to 1200m below surface level (bsl) are being drilled in the Geneva area to tap potential targets in the carbonate Mesozoic units and at least three additional wells, down to 500m bsl will target the Molasse sediments in the Bern area next year. These wells allow subsurface exploration and characterization and will provide data, used for detailed THMC modelling to assess the thermal energy storage potential at the two sites in Switzerland. The results of such numerical modelling are combined with energy system analysis to quantify the waste heat availability and heat demand and hence optimize the production and injection operations. The outcomes of the coupled assessments will aid in designing the integration of the new installations into the district-heating network. Legal framework improvements, based on complete technical evaluation and on the best-practice sharing with the other European partners, will be an enabling tool to accelerate the implementation of the HT-ATES systems, while business modelling helps calibrate the economic feasibility of the projects and helps industrial partners to plan future investments.

1. INTRODUCTION

HEATSTORE is one of nine projects under the GEOTHERMICA – ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by:

- Advancing and integrating different types of underground thermal energy storage (UTES) system in the energy landscape,
- Providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, and
- Addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

The 24 contributing partners from 9 countries within HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The combination of leading European research institutions, together with small, medium and large industrial enterprises, promotes bringing the tested technologies to market.

The deployment of renewable energy sources (RES), for both power and heat production, is accelerating in Switzerland. This trend will continue, thanks to the passing of the 2050 Swiss Energy Strategy on May 21st, 2017. The new energy strategy aims at gradually phasing out nuclear power by reducing the energy consumption and increasing electric and heat generation from renewable energy sources. In Switzerland the total energy consumption decreased by -0.4% between 2016 and 2017, reaching 849'790 TJ. More than 60% of the energy consumed was supplied by fossil fuels, 12% by renewable energy sources and 24.8% was covered by electricity. Of the energy consumption, 27.8% was for households, 18.5% for industrial activities, 16.4% for services and 36.3% for mobility. UTES systems, and more specifically ATES systems, can provide a modular and flexible solution to contribute to the 2050 Swiss Energy Strategy by storing waste heat in aquifer formations and then delivering it in high demand seasons.

The Swiss consortium is composed of 2 industry partners – Services Industriels de Geneva (SIG) and Energie Wasser Bern (EWB) – and 4 universities – Universities of Geneva, Bern, Neuchatel and ETH Zurich - working on two projects in the Geneva and Bern Cantons.

The HEATSTORE Switzerland project aims at assessing the feasibility and the potential of HT-ATES at two sites located in the Cantons of Geneva and Bern, respectively. The main pillars of the projects are:

- Subsurface characterization by data acquisition from exploration wells and surface exploration, and static and dynamic reservoir modelling
- Energy system scenarios modelling and integration
- Monitoring and models validation
- ATES economic viability assessment
- Swiss legal framework adaptations
- Dissemination and communication

Data collected in the framework of the industrial geothermal exploration and development activities driven by SIG and EWB are combined to produce a number of predictive integrated models that will allow evaluation of the technical-economical-legal-social feasibility of HT-ATES projects within Switzerland.

The starting data to be evaluated are: (a) the energy system configuration in terms of waste heat availability and heat demand, and (b) the subsurface conditions. These data are combined to develop energy system scenario models and 3D subsurface petrophysical models. The results serve as inputs for predictive thermal-hydraulic-mechanical-chemical (THMC) dynamic models. Such models allow assessing the technical feasibility of HT-ATES systems at the two pilot sites. These models will be calibrated and validated when new data become available during subsurface prospection, exploration and implementation phases. Once the THMC models are validated, they will allow for assessment of the economic feasibility, which will also be linked to the improvement and adaptation of the existing Swiss legal framework. Dissemination and communication/outreach activities aim to improve public acceptance.

1.1. The Geneva project

The goal of the Geneva project is the assessment of the heat storage potential for the development of an HT-ATES system connected to a waste-to-energy plant operated by Services Industriels de Genève (SIG). This plant uses domestic wastes to produce energy and emits excess heat to the environment, which could potentially be stored in the Geneva subsurface and delivered to final users during seasons of high heat demand. The overall goal of the project is the subsurface characterization and energy system integration constrained by drilling and testing at two different locations (GEo-01 and GEo-02) where two potential reservoirs in Cretaceous and Jurassic limestones are located at depths between 500m and 1100m. At this stage, the work is focused on the subsurface characterization and energy system scenarios modelling, which will be coupled to economical, regulatory, and social constraints, to potentially lead to a commercial implementation of the system in a future stage. GEo-01 was drilled in 2018 and reached a depth of 744 meters aiming at the Lower Cretaceous and Upper Malm units, cut by a NW-SE oriented strike-slip transpressive zone as identified on reflection seismic data. GEo-02 is planned to reach 1100 meters bsl in depth and will drill into the Upper Malm limestone consisting of Kimmeridgian reef complexes and a sequence of thrust faults, where fracture conditions can enhance the permeability of the target formation.

A modular and holistic approach is developed addressing the following aspects:

- Resource assessment and reservoir characterization is achieved by drilling of two deep wells, collecting well data, running laboratory experiments, developing and running in-situ test protocols adapted for determining key reservoirs parameters in the context of an HT-ATES, and running production/injection tests reproducing the envisaged full-scale future operating conditions.
- Reservoir development scenario modelling in order to provide industrial developers with the necessary background knowledge to assist their decision-making process.
- Energy system scenario modelling to integrate an HT-ATES system into the existing network.
- Economic modelling aiming at reducing the risk and the costs of running an HT-ATES system focusing on the sustainable development of the project.

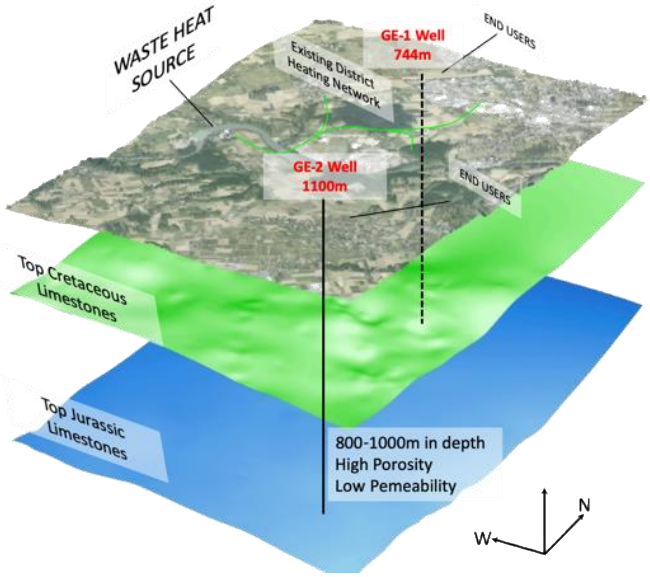


Figure 1 – Cartoon of the Geneva project

The Geneva area is geologically complex and challenging for HT-ATES, due to the significant topography at the boundaries potentially imposing artesian hydraulic conditions, strike-slip and thrust faults leading to compartmentalization of aquifers and providing potential leak-off structures, inclination of aquifers raising the question of the role of buoyancy in storage, and variable sedimentary facies within the aquifers leading to heterogeneity. Therefore, assessing these complexities can help to inform: (a) decisions about where and how many additional wells are drilled, (b) how the district heating network will be designed and developed, (c) the definition of business models and (d) the overall sustainability of the ATES system in Geneva.

The assessment of site-specific geological layers to be utilized in the design of the Geneva ATES system is based on data gathered from surface prospection and exploration wells in the area and thus at least three main development strategies have been identified:

- **Geologic complexity**: The study area is characterized by strong heterogeneities in terms of reservoir petrophysical properties mainly dominated by stratigraphic, sedimentological and diagenetic processes as well as by presence of fault corridors, which have been identified according to 2D reflection seismic data. The role of such faults zones in the study area is still uncertain as they may either act as preferential flow paths for groundwater or act as impermeable barriers causing compartmentalization of the potential HT-ATES reservoirs.
- **Environmental impact**: The main potential environmental impacts associated to production and injection operations that can affect the Geneva area are surface deformation and seismicity. The HT- ATES system will perform under an operational strategy based on seasonal loading/unloading cycles of the aquifer, which can theoretically cause ground uplift during loading and subsidence during unloading. Seismicity in geothermal projects is commonly associated with injection in deep reservoirs. Considering the seasonal storage/production operations planned, and although there are no records of seismicity associated to ATES projects, it is an element of impact that has to be considered, modelled, and monitored.
- **Operational risk**: The main operational risks are associated with the chemical processes of mineral dissolution and precipitation that can occur in the reservoir, and corrosion and scaling in the wells and in the surface installations (i.e. pipes, heat exchangers). Such risks can strongly affect the life-time performances of the HT-ATES system and therefore have to be quantified to identify the best mitigation strategy.

These three challenges are to be tackled by establishing a workflow that includes a flexible reservoir modelling approach and corresponding application tools. Such a combination will help predict reservoir performance and support SIG in designing the HT-ATES systems according to the heat availability and demand fluctuations over the life-time of the project.

Three basic conceptual approaches will be combined into the modelling workflow to help identify the optimal operational conditions, mitigate the environmental impacts, and minimize the operational risks:

- Thermo-Hydro (**TH**) modelling will focus on the dynamic thermal flow scenarios to optimize the storage and production operations according to thermal power inputs in terms of heat supply and demand, and to the available 3D geological and petrophysical static model
- Thermo-Hydro-Mechanical (**THM**) modelling will aim at evaluating the effects of the HT-ATES Systems on ground surface deformation and seismicity. Efforts will focus first on predicting the effect of the 6 to 8 months of production tests at GEo-01 and will be validated by the monitoring techniques which will be applied (i.e. GPS levelling, INSar, Micro earthquake monitoring network). Once the operational scenarios are defined, THM modelling will also be used to predict longer-term uplift and subsidence due to HT-ATES operations.
- Thermo-Hydro-Chemical (**THC**) modelling will serve as a crucial tool to assess the chemical reactions which might occur in the reservoir (i.e. mineral dissolution and precipitation) during operations and that can affect the HT-ATES performance (e.g. scaling and corrosion). Reactive transport modelling will be based on geochemical inputs from the ongoing groundwater monitoring survey, and on laboratory experiments on cores under in-situ conditions.

1.2. The Bern project

The pilot project in Bern aims to store waste heat from the nearby Bern-Forsthaus power plant. The power plant is operated by the local utility company Energie Wasser Bern (EWB) and contains a combined-cycle plant, waste-to-energy plant and wood-fired power station for electricity and heat production. For the pilot heat storage system, three wells will be drilled to a depth of ~ 500 m deep will be drilled to reach sandstone layers of the Lower Freshwater Molasse (USM). The goal of these wells is to assess the feasibility of the HT-ATES system and, if the results are encouraging, more wells will be drilled after the HEATSTORE project, to realize a fully functional heat storage system with an injection temperature of max. 120 °C and an expected output of 7 – 10 MWth.

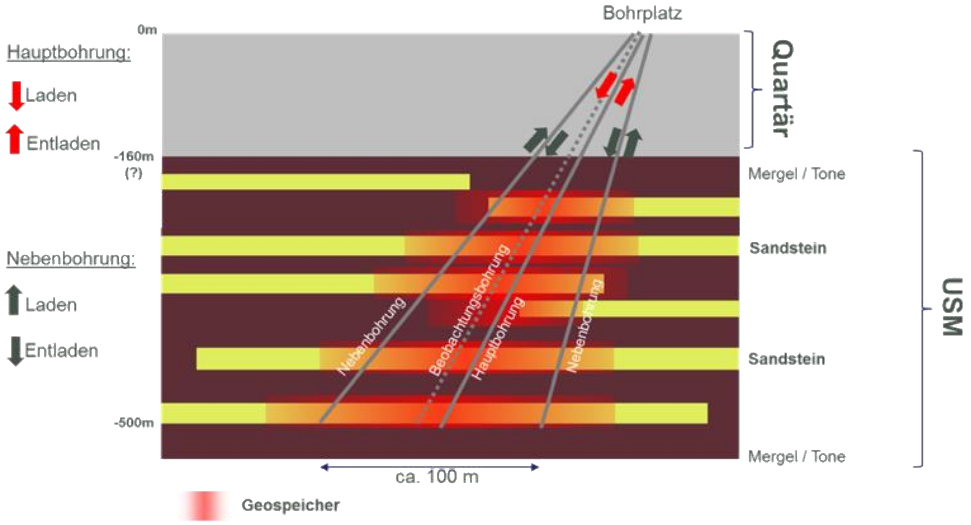


Figure 2 – Schematic representation of the Bern project

The main drivers of this project are:

- Energie Wasser Bern (EWB) is a strong industry partner and the local utility company in the region of Bern.
- An increasing heat demand and a planned expansion of the existing district heating network in the city of Bern.
- The commitment of the city of Bern, owner of EWB, to support renewable energy technologies; to improve overall efficiency in energy production and to reduce CO_2-emissions.

In order to operate the future ATES in a safe and optimized manner, the following aspects are planned to be investigated by modelling:

- Subsurface flow dynamics and heat transfer in relation to the storage concept: To this end, a preliminary operation mode was defined. Additionally, coupled hydraulic and thermal modelling will be performed with different operation parameters (changing temperature, loading- and unloading time) in order to optimize overall storage capacity and performance.
- Additionally, Radial Jet Drilling is planned to improve reservoir transmissivity in case the natural reservoir transmissivity turns out to be insufficient. Radial Jet Drilling allows drilling / jetting of small diameter laterals (Ø ~1") up to 100 m from a vertical wellbore. Up to six laterals can be horizontally jetted from one point in the wellbore in different directions.
- It is well known that fluid-rock interactions can affect overall system performance. Therefore, chemical reactions and their impact on environmental and operational aspects are constrained, focusing on chemical fluid-rock interaction during loading- and unloading cycles.
- Poro- and thermo-elastic effects and their impact during loading- and unloading cycles will be assessed by investigating the impact of expansion and contraction within the reservoir with respect to reservoir stability and shear processes and at the surface with respect to uplift and subsidence. In addition, poro-elastic effects are modelled in order the investigate investigate changes of effective stress within the reservoir. If these changes are significant, innovative seismic surveys (3D-seismic, VSP) can help to image reservoir geometry.

2. ACTIVITIES CARRIED OUT IN THE FIRST PHASE OF THE HEATSTORE SWITZERLAND PROJECT

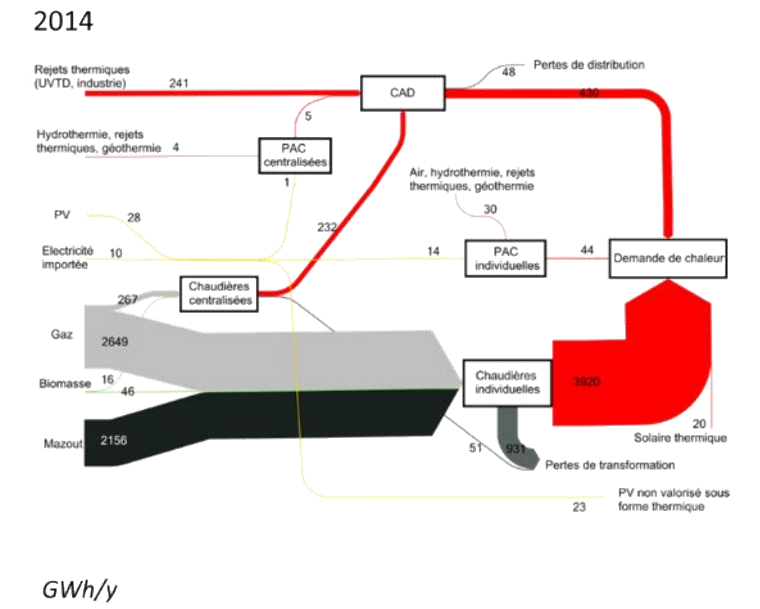
The first year of the activities carried out focused on 3 main tasks:

- Definition of the energy systems scenarios
- 3D static modelling
- 3D preliminary TH-THM-THC predictive dynamic modelling

2.1. ATES and district heating integration for the Geneva site – scenarios construction

2.1.1 Energy context

Currently, more than 50% of total final energy at Geneva is used to cover space heating (SH) and domestic hot water (DHW) demand (Quiquerez et al., 2017). Despite the important heating demand and the high energy density (Quiquerez, et al., 2017), only 10% of total thermal demand (450 GWh/yr.) is covered by district heating networks (DH) (Figure 3 upper diagram).



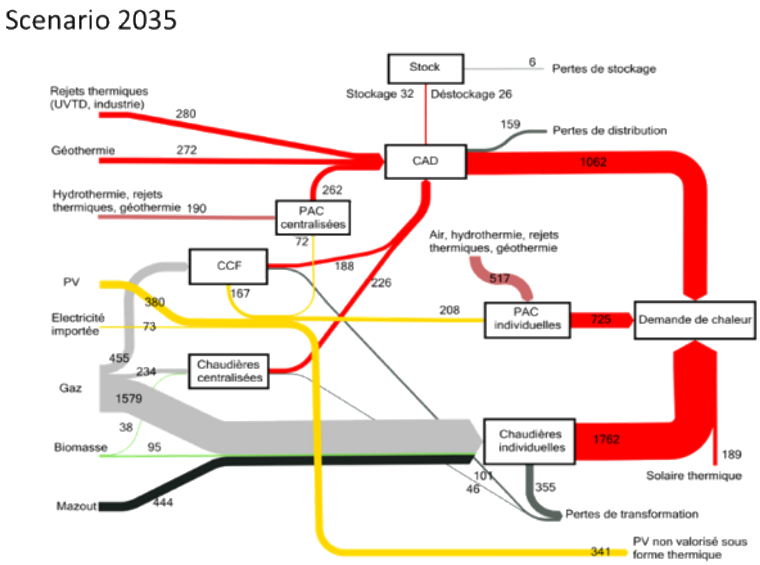


Figure 3 - - 2014's heat demand and thermal energy scenario for 2035 in GWh/yr (modified from Quiquerez, 2017)

It is planned by 2035, about 30% of total heating demand (1'050 GWh/yr.) will be covered by DH, with at least 80% of it supplied by renewable energies. A prospective scenario for 2035 is shown in Figure 3 (lower diagram), where one can see the increasing importance of renewables in the heating energy system.

As shown in Figure 4, DH will have a key role for large renewable energy integration. For example, deep geothermal exploitation will be shared at Cantonal level, which enables to overcome technical, spatial and economic constraints. Besides, since DH networks will be the charging/discharging facility for the aquifer thermal energy storage (ATES), it is crucial to evaluate the supply/demand evolution and the ATES integration in this evolving context.

At present, the DH system is supplied by the urban solid waste incineration plant (49 MW) and centralized gas boilers (200 MW). New thermal production capacities are under planning to ensures the required renewable share in the DH:

- the refurbishment of the combined heat and power (CHP) on urban solid waste incineration plant (57 MW by 2024),
- the construction of a CHP on waste wood incineration plant (12 MW by 2023),
- the construction of large-scale high-temperature heat-pump (HP) plants based on sewage water (25 MW by 2023 and 50 MW by 2035) and lake water (5 MW by 2023),
- the construction of 3 wood boilers (5.5 MW by 2023).

The geothermal potential on the other hand is still unknown in Geneva canton. Conservative values have been used (from 4 MW by 2024 up to 25 MW by 2035) in this prospective exercise.

The existing thermal network currently operates at a high temperature regime (120°C/75°C in wintertime and 90°C/75°C in summer), while the major extension towards the south of the Canton is planned to work at lower temperature levels (90°C/55°C and 75°C/55°C). This is important as the DH temperatures will drive and set the ATES charging/discharging temperatures.

2.2.2 Charging/discharging scenarios construction

The first question to be addressed when designing the integration of an ATES into a DH is how should the ATES be charged and is the discharge into the DH feasible? The DH must be able to accept the extra energy from the ATES and the charging energy must be available at relatively low cost in order ensure the economic feasibility of the project.

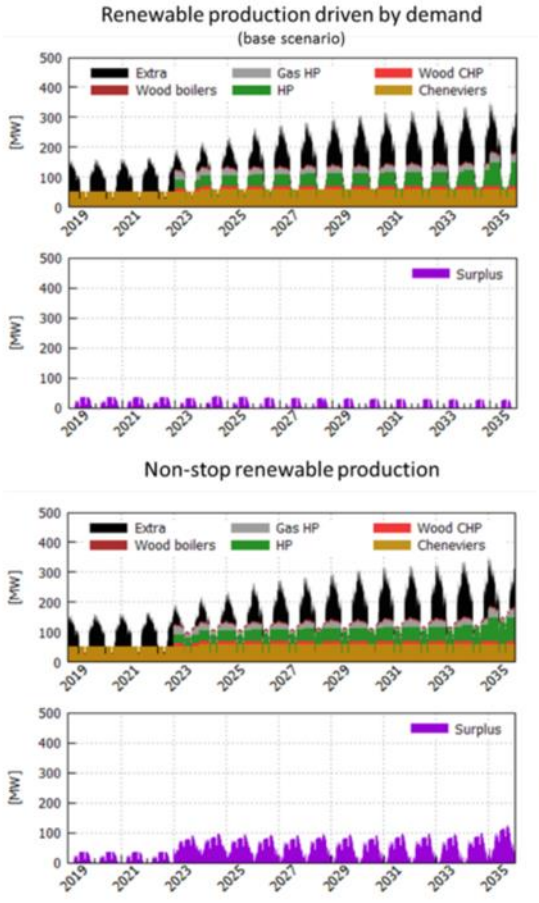


Figure 4 - DH energy mix evolution (upper figures) and energy available for ATES ("Surplus" at lower figures) for two different renewable production scenarios.

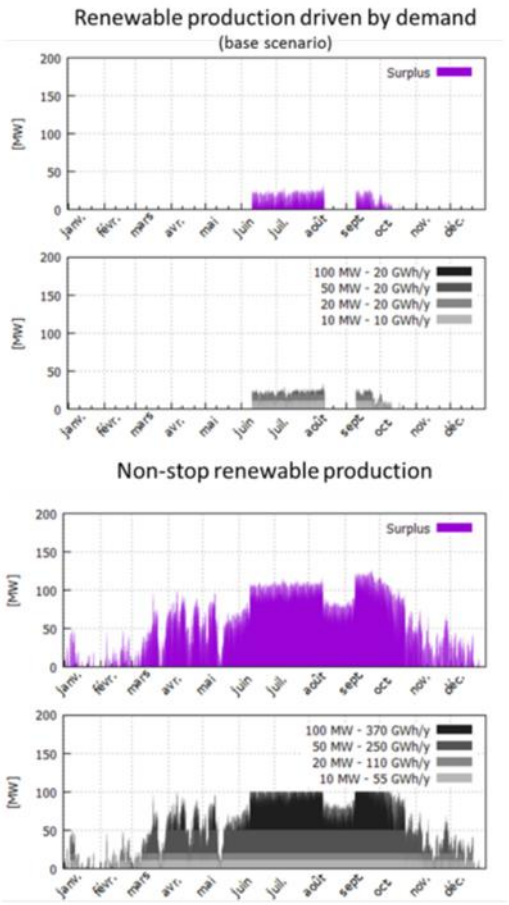


Figure 5 - Heat power charging limitations and corresponding energies by 2035 for two different renewable production scenarios.

Specifically, for the ATES system studied in Geneva, different charging/discharging strategies are proposed to test storage thermo-chemical reactivity and its integration with the Cantonal energy system. Constant charging temperatures are set to 90°C, 75°C and 55°C, which correspond to the DH summertime temperature levels and express the uncertainties regarding the future ATES location. At the same time, two charging scenarios are proposed: i) CHP surplus storage; ii) CHP surplus summed up to the heat production from HP plants based on sewage and lake water. The goal of the second scenario is to upgrade the temperature of these resources in summer when European electricity has the lowest CO_2 content, enhancing the HP performance during wintertime.

Based on the assumptions mentioned before, the available energy for storage is explicitly shown in Figure 4, where the two charging scenario are shown. For the non-stop renewable production scenario, the annual storable energy available varies between 100 and 200 GWh, while for the base scenario, it is always lower than 70 GWh/year.

After predictive THCM results, new constraints will be added to the model, for example charging/discharging power limitation (Figure 5) and temperature limits for ATES based on mineral reactions, uplift due to thermal expansion etc.. The idea is to create a retro-alimentation process: results from geology models are used as inputs for energy models and vice-versa. Besides, the geo-localisation of supply-storage-demand, the merit-order between different heat plants and the possible concurrence between renewables and the ATES system will be investigated later on in the project.

2.2. 3D reservoir static reservoir model

2.2.1. The Geneva project

The 3D reservoir modelling activities for the Geneva site are carried out by the University of Geneva and until now have focused on the subsurface 3D static modelling at the GEo-01 site. All interpretations and modelling were performed using Schlumberger's Petrel 2018 seismic interpretation software. The available 3D regional geologic model available from the GEOMOL project (www.geomol.eu) has been improved in terms of data accuracy and resolution over a volume of 2x2x0.8km surrounding the GEo-01 well. Analyses of a suite of a subsurface dataset comprising of 2-D seismic reflection data, integrated with petrophysical data and well reports from the newly drilled GEo-01 borehole coupled with interpretation from the GEOMOL Project was used to constrain the initial 3-D geological model. This first version of the model includes simple geometries representing the key depth intervals derived from formation tops and the GEOMOL interpretation. In the first stage of modelling, all horizons were considered as horizontal surfaces thereby discounting any subsurface structural configuration for simplicity in the first stage of modelling. To decipher suitable intervals for thermal storage, several parameters have been considered and computed. Most importantly the lithology, shaliness of the formations (for the Molasse) and porosity and permeability (fracture and fault network derived from the well report). Intervals were hydrocarbon indices were mentioned in the end drilling report were excluded as may have implication on the success of the thermal storage operation (Eruteya et al., 2020). Extrapolation of properties beyond the interval logged in Geo-01 was achieved by considering lithologies recorded in the well report and also the Jurassic reef interval was considered as a 50 m thick interval with the upper Jurassic. The Upper Malm carbonate reef complex thickness (not reached by GEo-01) used in this model is taken from previous studies.

The model consists of 15 surfaces and 14 units, 5 of which have been identified as potential target intervals for heat storage.: 1 unit within Tertiary Molasse, 3 units within the Cretaceous limestones and 1 unit within the Jurassic limestones. The geological model developed was then populated with petro-physical and thermal properties for subsequent numerical heat flow and predictive THMC models for the Geneva Basin (Rusillon, 2018).

Stratigraphic and geophysical well data have been interpreted to produce a geological and structural 3D model, which has been populated with petrophysical data (porosity and permeability from Rusillon, 2018) according to the following studies (Figure 6:

- Interpretation of seismic data to reconstruct the fault architecture and improve the identification of the main potential target units/structures
- Diagenetic characterization of Lower Cretaceous and Upper Jurassic Units based on cuttings analysis
- Mineralogical and petrographic characterization of Lower Cretaceous and Upper Jurassic Units based on cuttings analysis and correlation with surrounding wells
- Fracture network modelling to produce a discrete fracture network model using geomechanical (in collaboration with University of Neuchâtel) and stochastic methods (Lo, 2019)

This geological and structural model will serve as the framework for future implementation of thermal properties for subsequent numerical heat flow and predictive THMC models for the Geneva Basin.

Additionally, a water sampling campaign across the Geneva Basin was carried out in December 2018 to improve the understanding of the hydrogeological processes controlling water circulation in the study area. The regional hydrogeological model is currently being developed together with University of Bern.

University of Geneva has started working on the GEo-02 well, where the main potential target unit has been identified as the Kimmeridgian Reef Complexes at the base of the Upper Jurassic. This formation, which was not reached by the GEo-01 well, is known to present favourable conditions in terms of porosity and permeability. Its vertical extent can reach up to several tens of meters and its lateral continuity is discontinuous but can reach up to 1km in width. This unit is potentially very promising also thanks to the presence of impermeable formations above and below it that might prevent regional groundwater flow through the reservoir. At present, the information available is scarce but University of Geneva carried out two studies on outcrop analogues:

- Petrographic, mineralogic, diagenetic and geochemical characterization of the Reef Complex unit in the northern and southern part of the Geneva Basin (Makhloufi et al., 2018).
- Drone photogrammetry on a selected outcrop to assess the vertical and horizontal extent of the Reef unit. Data have been processed to produce preliminary porosity and permeability 3D models. This study will continue in summer 2019-2020 on other outcrops in the Geneva area and will then be validated and calibrated by GEo-02 data .
- Diagenetic, mineralogical and petrographic characterization of core samples collected in the La Plagne Quarry (France).

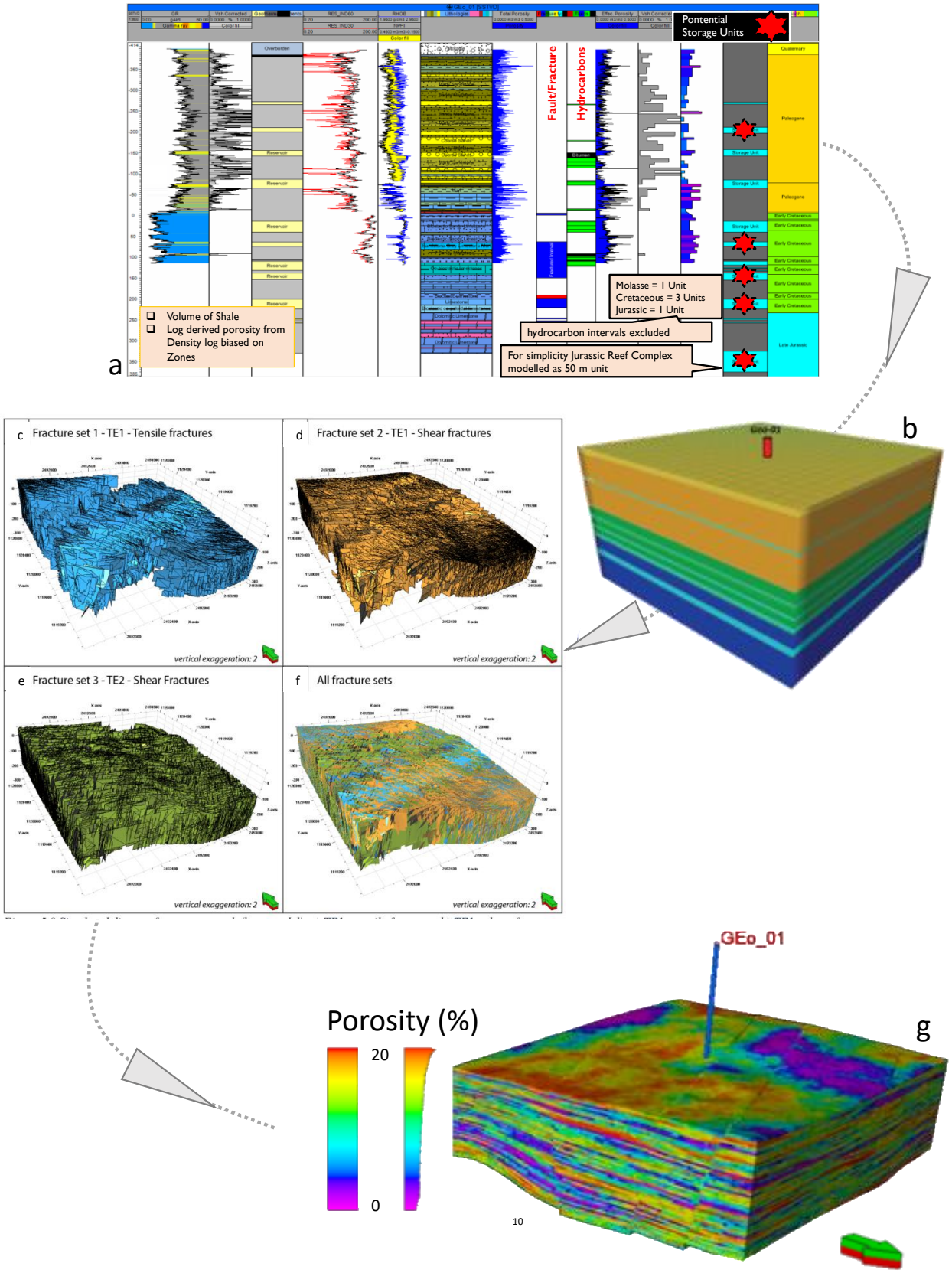


Figure 6 - a) Preliminary interpretation of GEo-01 Well for candidate intervals for thermal storage (denoted by the red star) and b) 3D model. (d-f) simulated discrete fracture network at the GEo-01 well. (g) Porosity model

2.3. Geomechanical characterization

The objective of this study carried out by the University of Neuchatel is to characterise the fractures, the mechanical characteristics and the stress state of the formations present around the first exploration well GEo-01. We base our analyses primarily on logging data.

We aim at constraining the reservoir geomechanical properties controlling the groundwater flow and the heat transport, as well as to evaluate the geothermal potential of the fractured limestone reservoir (Koumrouyan, at al., 2019).

2.3.1. Data acquisition and analysis

2.3.1.1. Fracturing analyses

Logging has been performed in the well, including optical and acoustic televiewers (Figure 7). These images allow the identification of fractures and the determination of their orientation, dip angle and aperture. This data is the base for the development of a fracture model for the drilled units.

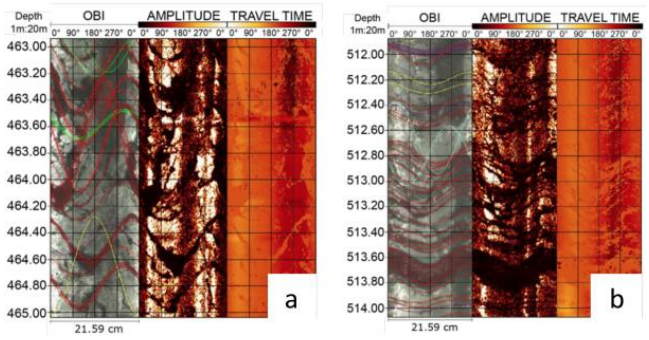


Figure 7 - Optical televiewer (left), acoustic televiewer amplitude (middle) and transit time (right) data displaying fractures developed in limestone rock in the GEo-01 well.

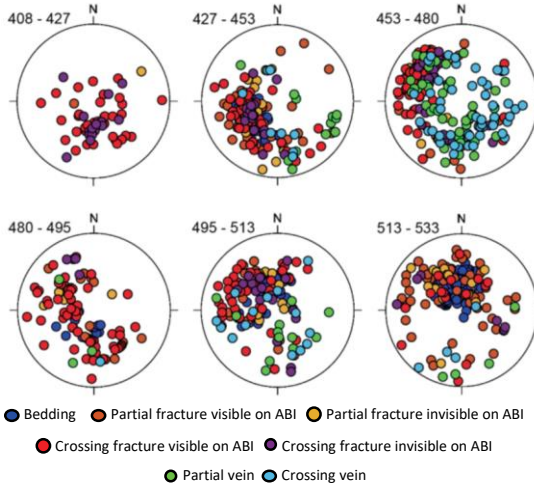


Figure 8 - Stereographic projection of the fracture poles (lower hemisphere, equal area) according to stratigraphic limits.

The results of fracture identification are presented in the following stereonets, separated according to lithological units (Figure 8). The less steep features are interpreted as bedding. We observe that the bedding orientation is quite variable with a tendency to rotate from the northeast toward the south with increasing depth. Moreover, a section between 460-480m (Figure 9) is characterised by open fractures with steeper angle and can be interpreted as a fault zone crossing the borehole.

Two working hypotheses could explain the variation in bedding orientation and dip direction variations: a cross-stratification of the bedding which is common in the Cretaceous (sedimentary hypothesis), or the presence of some tilted blocs related to a flower structure (tectonic hypothesis). Further analyses will help to understand the origin of this variability.

2.3.2. Borehole shape analyses

Transit time measurements made by the acoustic tool can be converted into borehole radii to analyse the shape of the well (Schlumberger Ltd, 1991). Well ellipticity, i.e. the ratio of the major and minor ellipse axis, and instability can be assessed and related to the orientation of the principal stresses.

We converted the transit time to radii for the GEo-01 well acoustic televiewer. The fluid velocity has not been measured. Thus, we calibrated our conversion on a four-arms caliper log run in the well. The transit time data for the well GEo-01 are noisy and contain numerous incorrect evaluations of the returning wave, particularly in fractured area with low amplitude data. This is visible in Figure 8 where homogeneous orange areas are visible and correspond to improper evaluation of the transit time. We filtered these improper data in order to keep only data representing a real well radius. This left us with an incomplete geometry of the wellbore, but nevertheless sufficient to evaluate potential well ellipticity. We did this evaluation by fitting ellipses on reconstructed borehole sections using a stable direct least square fit algorithm by Halír & Flusser, 1998. This allowed us to evaluate the orientation of the best fitted major axis and the ellipticity.

The expected output for a well is a highly variable and random orientation of the major ellipse axis and a low ellipticity. For GEo-01 this is the case from 380 to 410 m depth, (Figure 9). However, for some sections, we observe that the borehole shows a stable and preferential orientation of the major axis, such as between 430-445 m. Such behaviour is yet unexplained and could be related to creeping under far field stress conditions and thus, if this mechanism is validated, could be used as an indicator of the in-situ principal stresses directions. Other sections present a more variable orientation of the ellipse, maybe related to the presence of karst or open fractures. Identification of correlations with the lithological units may also help to explain the variations of orientation and ellipticity of the well.

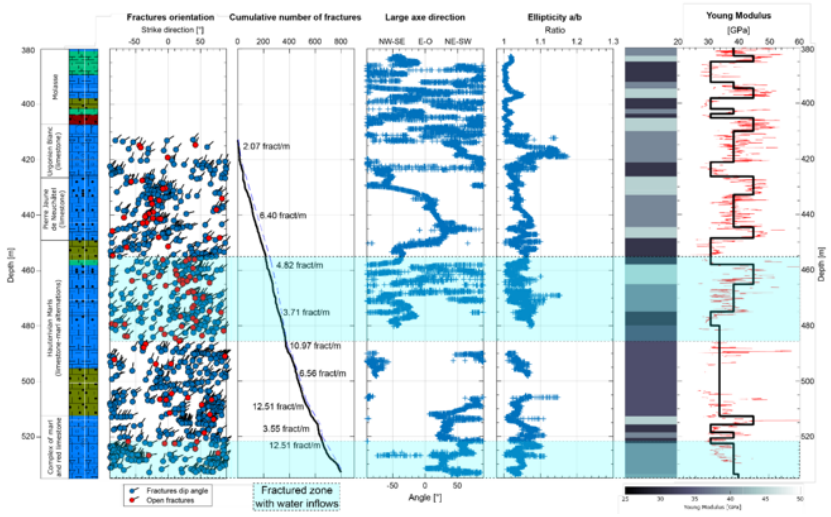


Figure 9 - Fractures characterisation (strike orientation and fracture intensity), borehole shape analyses (large axis direction and ellipticity) and Young's modulus values (red line) as function of the rock strength and lithology along the borehole GEo-01. The Young's modulus black line represents the median values used for numerical simulations.

2.3.3. Mechanical properties

Mechanical properties and rock strength are obtained from the sonic and density logs (Schlumberger Ltd, 1991). Elastic moduli are fundamental to estimate the stress state, strain and rock strength surrounding the borehole (Gudmundsson, 2011). Indeed, the stiffness of a rock and more particularly stiffness contrasts between formations can induce some important variations of the stress, with stress concentration in some stiffer layers (Bourne, 2003; Corkum, et al., 2018). Stiffness also controls fault nucleation and propagation (Roche, at al., 2013).

Initially, we estimated a stress model based on Stephansson & Zang, (2012). The observation of the well stability and independent assumption of the wellbore wall strength derived by laboratory testing and sonic logs, allow to refine possible bounds on the stress magnitude and to refine the initial best estimate stress model.

In integration with the observed characteristics of the natural fractures, the mechanical properties help therefore to understand how the production rate influences the opening or closing of fractures, and how they can change the permeability surrounding the well. Such observation can be correlated with the inflow observations during the drilling of GEo-01 (Figure 9).

2.4. Dynamic reservoir modelling

The goal of this task is to simulate underground fluid flow, heat transport, geomechanics, and chemical reactions to estimate the efficiency, feasibility, and safety of using the Geneva subsurface as an HT-ATES site. For conceptual, mathematical, and computational convenience, we have divided our simulation efforts into three main groups: TH = Thermal-Hydrological, THM = Thermal-Hydrological-Mechanical, and THC = Thermal- Hydrological-Chemical. TH simulations will focus on (a) assessing thermo-hydrological challenges to heat storage in the complex subsurface of the Geneva Basin and (b) on quantifying overall thermal efficiency using plausible-yet-simplified realizations of the underground heterogeneity (i.e. formation layers, faults and fractures) as well as pre-existing hydrological conditions (e.g. ground water flow). TH simulations will also essentially act as a screening process to determine scenarios to be further simulated by THM models, which in turn will focus primarily on locating and quantifying mechanical-related safety issues (e.g. ground surface deformation and subsurface stresses and strains). THC-based simulation scenario development will also be aided by insight from TH and THM models, and the results will help to anticipate issues related to mineral dissolution and precipitation reactions occurring in the entire ATES system (e.g. porosity and permeability decrease due to carbonate precipitation, carbonate scaling at the heat exchanger, etc.).

2.4.1. Thermo-Hydraulic TH reservoir model

TH simulations require a computational grid based on an arbitrarily-detailed geometry. The base geometry can be created in any CAD model, and in the current case it was created using the Petrel software. After trimming surfaces defining the different geological entities to the modelling size, they are then exported and subsequently imported into a 3D meshing software, ICEMCFD.

The geometrical model volume is then tessellated by unstructured/irregular tetrahedrons with reasonable resolution control, thus honoring material interfaces between rock-types, fractures, and well trajectories. Triangles are used to tessellate lower dimensional representations (i.e. interior surfaces) of fractures, and line segments to tessellate well completions. The latter triangles and line segments are often referred to as LDE's (Lower Dimensional Elements), since they possess at least one dimension lower than the maximum dimension used to represent the global domain.

The resulting complete tessellation is populated with all known material properties, honoring the information provided by Univeristy of Geneva (see section 2.2.1).

ETHZ identified the main factors at play be considered should include buoyancy, groundwater flow, multiple aquifer storage, and faults/fractures/reef structures. Simulation assessment increments were then defined through a series of ongoing and iteratively-improved scenarios. Subsequently, seven modelling scenarios are now under development:

- **Scenario 1:** A "flat" model (i.e. no dip angle on any layer), synthetic but with characteristics relevant to the interpretation provided by University of Geneva, simulated with and without groundwater flow.
- **Scenario 2:** Based on Scenario 1 but introducing 15-degree dip angle on all layer surfaces, simulated with and without groundwater flow.
- **Scenario 3:** Based on Scenario 1, introducing reef structure in aquifer layer(s) of variable permeability, with and without groundwater flow.
- **Scenario 4:** Based on Scenario 1, introducing a synthetic single fracture only on the aquifer region with varying permeability and within 100 $[m]$ from the well, simulated with and without groundwater flow.
- **Scenario 5:** Based on Scenario 1, introduce faults of different types. In contrast to Scenario 4, this scenario may require more involved meshing depending on the type of fault (e.g. thrust, strike-slip with dilational step-overs)
- **Scenario 6:** Based on Scenario 1, introduce an auxiliary re-injection well at a variety of distances (i.e. 50 $[m]$, 100 $[m]$, 200 $[m]$, directly upstream in terms of groundwater flow from the location of the main injector well.
- **Scenario 7:** Based on interpreted data provided by University of Geneva and SIG with a certain degree of simplification, introduce the final accepted geometries of horizons and faults as well as petrophysical parameters distribution. This scenario will essentially be a more geometrically/geologically detailed and complex version of all combined scenarios above, focusing on the possibility of a fault/fracture flower structure existing in the vicinity of the main operating well. This scenario's final definition (i.e. there may be more than one) will likely be a moving target depending on results from other scenarios.

A sample of the results obtained for Scenarios 1 and 2 can be observed in Figure 10.

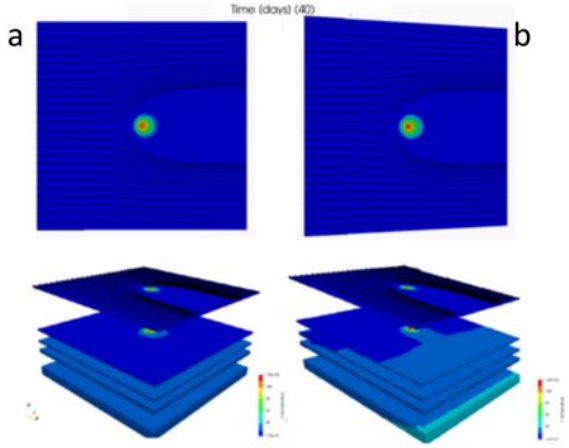


Figure 10: Snapshot of temperature results from Scenarios 1 (a) and 2 (b). The black lines represent the streamlines present due to groundwater flow. A slight drift can be observed in the top figures for the temperature signature established by the injector well present in the centre of the domain. The well penetrates all five aquifer layers shown in the bottom figures. These aquifers are also surrounded by other heat conductive layers of lower permeability (not shown).

2.4.2. Thermo-Hydraulic-Mechanic THM reservoir Model

The thermo-hydrological-mechanical (THM) and hydrological-mechanical (HM) modelling is motivated primarily by a desire to understand and constrain ground surface deformation, which is discussed in more detail in Birdsell & Saar (2020). Ground surface deformation can be caused by thermo- and poro-elastic expansion and is important because of the proximity of the HT-ATES sites to infrastructure and urban centres in Geneva and Bern. Surface deformation due to geothermal energy projects has caused infrastructure damage in the past (Sarychikhina & Glowacka, 2015) The conceptual model considers input from the energy systems scenarios and the 3D static geological modelling for Geneva. The numerical model uses the Multiphysics Object Oriented Simulation Environment (MOOSE) (Alger et al., 2019; Gaston et al., 2015). Two-dimensional THM and three-dimensional HM simulations have been run. We present the 3D HM simulations in this paper. We acknowledge that the HM simulations neglect thermal expansion and its effect on surface deformation, and plan to add thermal coupling to the 3D model in future work.

Figure 11 depicts a subset of simulation results that are presented in Birdsell and Saar (2020). The base-case results show that a large amount of uplift (>6 cm) is possible after a loading cycle that injects 50 L/s for 216 days. A simple sensitivity analysis shows that uplift is substantially diminished if auxiliary well(s) are included to balance the reservoir pressure, or if the aquifer permeability is increased by a factor of 100. Uplift is diminished marginally for a stiffer rock and/or if a deeper aquifer is selected. We conclude that two aspects of the HT-ATES site must be satisfied to avoid large amounts of surface uplift: (a) the HT-ATES system must include auxiliary well(s), and (b) the aquifer must have sufficient permeability. Several open questions remain: (a) where in the best place within the Geneva basin to build the HT-ATES system?, (b) what is the optimal well spacing?, and (c) how does the thermal expansion/contraction affect surface deformation? Future work involves expanding the model to include thermal coupling, more site information from the static geological model, and longer simulations of multiple loading and unloading cycles. We also plan to calibrate our model against data from a planned pumping test at GEo-01. This future work can further clarify HT-ATES site-selection and operational decisions, and this approach can also be applied to understand surface deformation in other contexts (e.g. geothermal energy and geologic carbon sequestration).

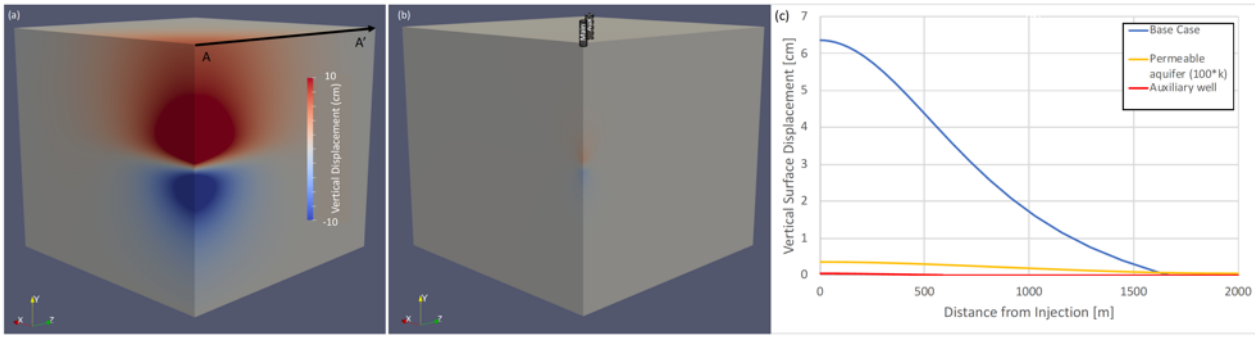


Figure 11: HM model results. Figures (a) and (b) show the vertical displacement for the base case scenario and a scenario where auxiliary wells balance the pressure, respectively. The approximate surface locations of the main well and auxiliary well are shown in (b). The simulations take advantage of symmetry. (c) The surface uplift versus distance from the well along line AA' for three scenarios: the base case, the scenario with the auxiliary well, and a scenario where the aquifer permeability is enhanced by a factor of 100.

2.4.3. Thermo-Hydraulic-Chemical THC reservoir characterization

The THC simulations are carried out using the state-of-the-art massively parallel subsurface flow and reactive transport code PFLOTRAN (www.pflotran.org). The simulations predict mineral dissolution/precipitation reactions both in the subsurface (reservoir) as well as in the surface installations (i.e. as mineral scaling). The chemical model will be kept simple at first by reducing the geological model to the relevant aquifers and simulating 1D flow along these units. Rather than solving for flow and heat transport explicitly, fixed velocity and temperature fields will be used. These fields can be extracted from the larger scale TH simulations. Although the model is simplified in terms of geometry, fluid flow and heat transport, it does include the full complexity of the chemical system. This model will be used for sensitivity tests involving different assumptions for flow and temperature conditions, corresponding to different operation schemes. Along with the simplified chemical model, a more complex, 3D thermal–hydraulic model will be constructed that includes the full stratigraphic sequence, injection/extraction of water into/out of the main well, flow from the uncased part of the well into the relevant units of the study sites, and a heat exchanger for cooling/heating the water at the well head. The final step involves integrating the simplified chemical model into the complex thermal-hydraulic model to run coupled THC simulations. In addition, the simulation of the Forsthaus site will also serve as a THC-benchmark problem run within the HEATSTORE project.

In order to better constrain kinetics of mineral dissolution and precipitation reactions, the team at the University of Bern will also perform laboratory experiments. The basis of these experiments are (a) information on formation water composition from the GEO-01 well and other wells and springs in the Geneva Basin as well as shallow wells drilled into the USM as part of the expansion of the main train station in Bern and (b) drill core samples representing the target lithologies (Kimmeridgian limestones in Geneva and Molasse sandstones in Bern) from a borehole in the La Plagne Quarry, France and the shallow wells in Bern, respectively. Experiments with variable physicochemical conditions (e.g. temperatures, fluid salinities, rock–water ratios) will be run to cover as many likely scenarios as possible. As the development of the two sites progresses, the experiments can be repeated under the actual conditions encountered in the subsurface of Geneva and Bern. This allows for a more accurate representation of the mineral reactions during HT-ATES by THC modelling.

3. CONCLUSIONS

This paper presents the results of the first year of the HEATSTORE Switzerland project. HEATSTORE is a 36-month project funded in the framework of the GEOTHERMICA – ERA NET Cofund and aims at assessing the technical-economical-legal-social feasibility and the implementation of HT-ATES systems in Geneva and Bern sites. The focus in this first phase has been on subsurface characterization and energy system scenario modelling. These two components provide input for predictive TH-THM and THC dynamic modelling. Future studies will include new data acquisition to calibrate and benchmark the current models. Once calibrated, these energy system models, static geologic models, and dynamic THMC models will eventually provide parameters for business case modelling and inputs for the adaptation of the Swiss legal framework to HT-ATES applications.

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